Captivating shimmer: The Milky Way is part of the system that is home to our Sun and an estimated 200 billion other stars. On a dark night, it shimmers like a nebulous ribbon on the firmament.

Archaeology of the Milky Way

The universe has billions and billions of galaxies, but only one that we can explore star by star in all its dimensions: our Milky Way. It can be thought of as a "model organism" for the formation and evolution of galaxies and is thus a key research topic in cosmology, and the research focus of the team working with **Hans-Walter Rix**, Director at the **Max Planck Institute for Astronomy** in Heidelberg. The researchers recently found indications that quite a number of earlier ideas about our galaxy have to be revised.

TEXT **THOMAS BÜHRKE**

A visitor approaching the entrance to the institute on Königstuhl hill near Heidelberg first notices hexagons chalked on the ground and joined together to form a huge honeycomb. These were left over from the last open house day and symbolize segments of the 39-meter-diameter main mirror that is to collect the light of distant stars and galaxies in the European Extremely Large Telescope in Chile from the next decade on. Astronomers at the institute are involved in developing two cameras for what will become the largest telescope on Earth.

But until it has been built, the explorers of the cosmos must be content with the telescopes that are currently available. This isn't necessarily a disadvantage, as recent years have shown that world-class research can be carried out even with relatively small instruments. The decisive factor here is that the astronomers have been using them to chart the entire sky continuously over many years.

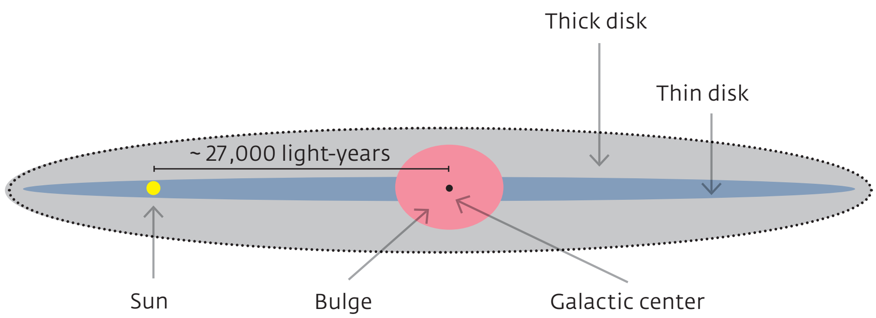
DATA MINING WITH 800 MILLION STARS

This treasure trove of sky survey data contains more information than can currently be analyzed and modeled. "In the very recent past, the quantity and quality of the data has doubled every one to two years," says Hans-Walter Rix. "Ten years ago, we had good spectra from around 8,000 stars; today, it's four million." For a study of the spatial distribution of the dust in the Milky Way, an international team led by Max Planck astronomers has now even analyzed data from almost a billion stars. This, too, has led the researchers to enter the business of big data mining. But what is the point of all this?

"If you want to investigate the evolution of galaxies such as the Milky Way, there are two possibilities," says Rix. "One is to observe galaxies that are increasingly far away from us." Because the speed of light is finite, looking into the distance is always looking into the past. It is indeed now possible to look over a billion years into the past directly at galaxies that formed one billion years after the Big Bang.

Galaxies at different distances from us are therefore at different stages of evolution. However, it is never possible to see one and the same galaxy at different times. Moreover, these galaxies

Photo: Corbis



Two views of the galaxy: The graphic on the left is an edge-on view of our Milky Way system looking from an angle. Two components can be seen in addition to the central bulge: a thin disk of stars close to the center plane and a thick disk that stretches farther into the outer region. Measurements indicate that the thick disk probably doesn't exist at all, but is based on a misinterpretation of data. The illustration on the right depicts a schematic plan view of the galaxy with several spiral arms. Our Sun is around 27,000 light-years away from the center.

are so far away that it is generally possible to make statements only about the system as a whole, since it isn't possible to recognize individual stars.

Rix went down a different path years ago. He investigates the galaxy that is closest to us: our Milky Way. "It is only in our own galactic home that we are able to observe the properties of individual stars in detail, in large numbers and in three dimensions," he says. Fortunately, our Milky Way is a typical galaxy, and what we learn about it can be generalized.

Around half the stars in today's universe are found in galaxies that are similar to our Milky Way in terms of size, mass and chemical composition. "It is something like the Rosetta Stone of galaxy research," says Rix. But how can the evolutionary history of our cosmic homeland be reconstructed if we can see it only in its present state?

The Milky Way is a dynamic system: stars have formed throughout its history. They move on different orbits around the galactic center, bearing some memory of their birth orbit. And they have distinctive chemical compositions, which can serve as chemical fingerprints. The idea now is to determine the properties of as many stars as possible and to deduce their past history with the aid of computer models.

This method is similar to the one used by scientists wanting to understand the migration of a demographic group over many thousands of years by analyzing genetic material. Insiders call it galactic archaeology, and it is now providing completely new insights.

A MASS MONSTER IS HIDING IN THE GALAXY

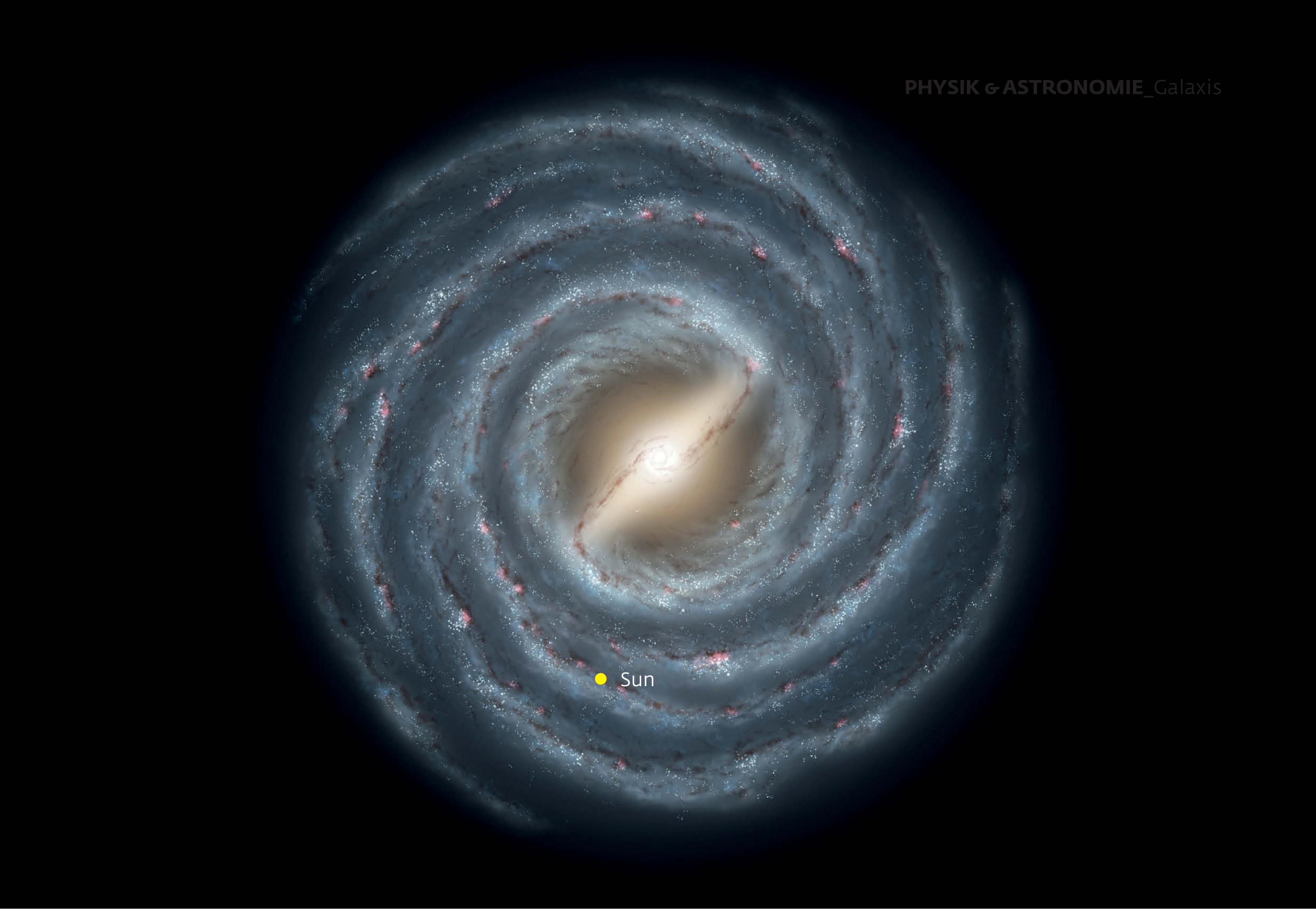
The Milky Way is a spiral galaxy with a diameter of around 100,000 light-years. It is subdivided into three regions. The very flat disk, just 2,000 light-years thick, is home to around 80 percent of all stars, and has a total mass of about 50 billion solar masses, along with clouds of dust and gas. Our Sun – only 80 light-years away from the center plane – also belongs to this largest population.

Around 15 percent of the stars are found in the central bulge. This is a spherical region around the center with a diameter of around 16,000 light-years. The central body itself is invisible. It is very likely a black hole with a mass of roughly four million solar masses. The remaining 5 percent of the stars move far above or far below the disk in the so-called halo around the central region.

Moreover, the view that the disk has two components – a thin one made up of stars close to the center galaxy, and a thicker one – has become textbook knowledge. The thicker component contains around 10 percent of all stars – including all the old stars – and extends far into the outer regions.

How the thick disk formed, however, remains a mystery. The favored theory assumed that the Milky Way collided with another large galaxy a long time ago, swirling up all the stars that were already in existence at that time

Graphic: MPG, based on original material from Gaba p/CC-BY-SA 3.0



and leading to the formation of the thick disk component.

All stars born after this postulated galactic cataclysm are now in the thin disk. Our Sun is one of them. However, the new measurements now indicate that the existence of such a clearly defined thick disk is probably a misinterpretation based on very limited data material.

Hans-Walter Rix and his colleagues had evaluated spectroscopic data from the Sloan Digital Sky Survey (SDSS). This sky survey is being undertaken with a 2.5-meter telescope at Apache Point Observatory in New Mexico (USA), to which the Max Planck Institute in Heidelberg makes a 25 percent contribution.

The spectra make it possible to determine the chemical composition of around 15,000 stars and group them into populations with the same abundances. The measurable abundances of elements form a lifelong fingerprint on the surface of the star and make it possible to estimate the age of the stars, just like in archaeology.

A crucial result of the SDS survey is that no strict subdivision into the two groups – the thin disk and the thick disk – is evident. The old school of thought that there was a collision with another large galaxy that is supposed to have formed the thick disk will probably have to be discarded. In the meantime, it seems most plausible that, during the turbulent early phase of the galaxy, stars were simply born in a disk that wasn't quite so thin.

Years later, Rix and his colleagues still occasionally come under fire at conferences for their new findings: many researchers don't like throwing accepted teachings overboard – especially not those that they themselves have developed.

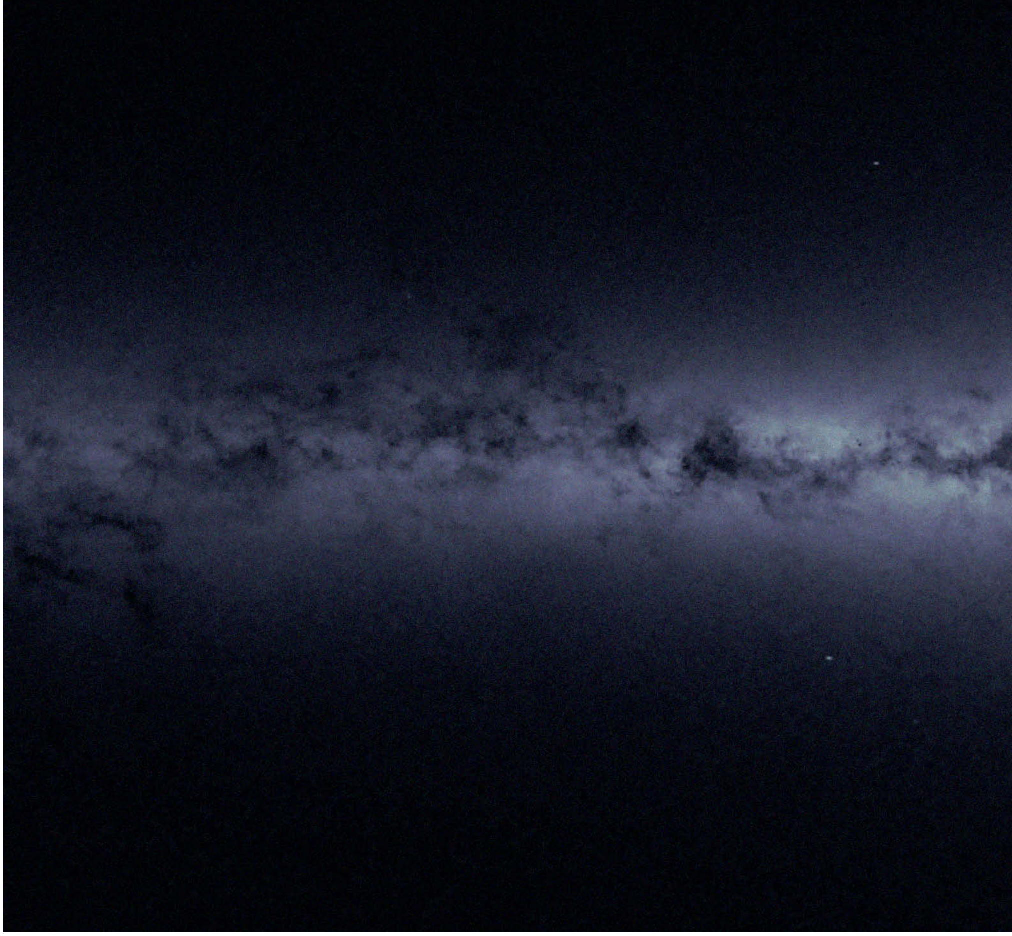
However, the treasure trove of data provided a great many more insights. Maria Bergemann, who completed her doctoral studies at the Ludwig-Maximilians-Universität Munich and recently became the Leader of the Stellar Spectroscopy and Populations Research Group at the Max Planck Institute for Astronomy, plays a crucial role here. Bergemann was able to determine the ages of stars and show that stars become increasingly younger the farther they are from the center of the Milky Way.

MIGRATION IN THE INTERPLAY OF THE SPIRAL ARMS

"This supports a scenario for the formation of the Milky Way that says that the star birth progressed from the inside outwards over the course of many billions of years," explains the young researcher. Galaxies like the Milky Way therefore start from an old center and grow gradually toward the outside – "similar to cities," adds Rix. In this respect, galactic archaeology has already borne many fruits.

However, nature came up with one fact that made it more difficult for the researchers to reconstruct the past: stars that don't have the expected relationship between age and chemical abundance are found in all belts of the

Photo: Robert Hurt/SSC/Caltech/JPL/NASA Robert Hurt



center of the Milky Way. "This finding can be explained by the fact that some stars don't remain on their original orbit around the center, but are able to migrate inwards and outwards," says Rix. New computer simulations support this scenario for the process of star migration.

The Milky Way is a spiral galaxy in which the spirals represent aggregations of gas and stars. If a star comes close to a spiral arm, it is attracted by the stronger gravity and accelerated – like a surfer on a big wave. If that star rides in front of this spiral wave, the star moves farther away from the center of the Milky Way onto a larger orbit. If, after a few hundred million years, this star happens to come under the influence of another spiral arm, but approaches it from behind, it becomes decelerated and moves inwards. Over billions of years, the result is that the star doesn't move on one simple circular orbit around the center, but migrates from one orbit to another – and thus conceals its place of origin.

"We want to try to reconstruct these orbital disturbances by looking for stars that have identical chemical compositions at different locations in the Milky Way," explains Rix. It can then be assumed that they originated in the same dust cloud and subsequently drifted away from each other through influences such as the gravity of spiral arms.

It looks as though the astronomers have to revise not only their ideas about the evolution of the Milky Way, but those about its formation, as well. This requires them to move mentally to the beginning of the universe.

DARK-MATTER PARTICLES EXERT NO ELECTRIC FORCES

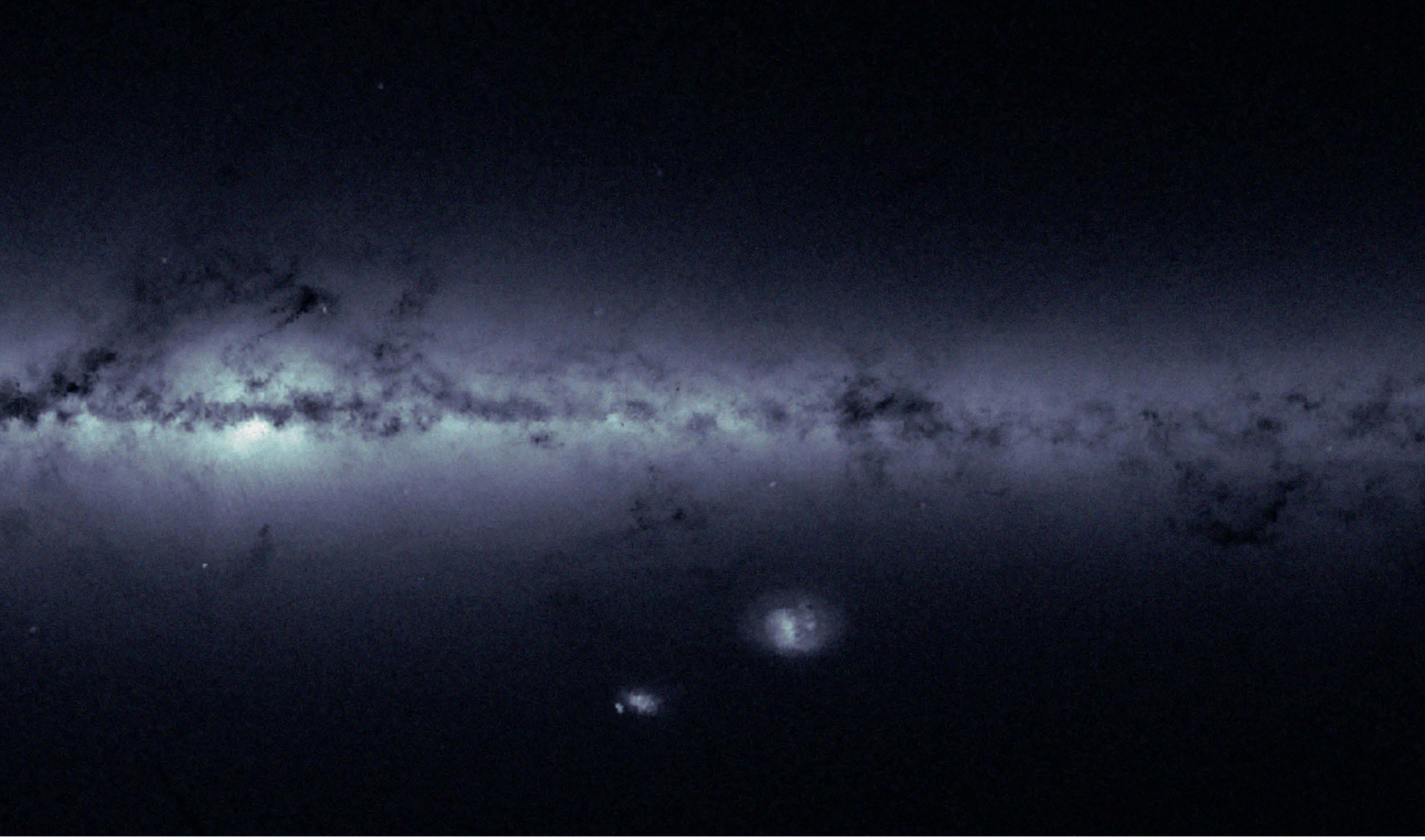
After the Big Bang 13.8 billion years ago, the primal gas comprised mainly of hydrogen and helium, on the one hand, and dark matter on the other, formed a relatively uniformly distributed haze. Although researchers still don't know precisely what dark matter is, everything currently points to it being an unknown form of elementary particle that can presently be detected only via gravitational effects. Particularly important is the fact that the particles don't exert any mutually repulsive electric forces. This was crucial at the beginning of the universe because the gravitational force tried to concentrate this matter into large lumps. But the hydrogen and helium nuclei were electrically charged and repelled each other. This prevented the hot gas from being compressed. The dark-matter particles, in contrast, don't exert any electric forces and clustered together to form huge clouds and long filaments.

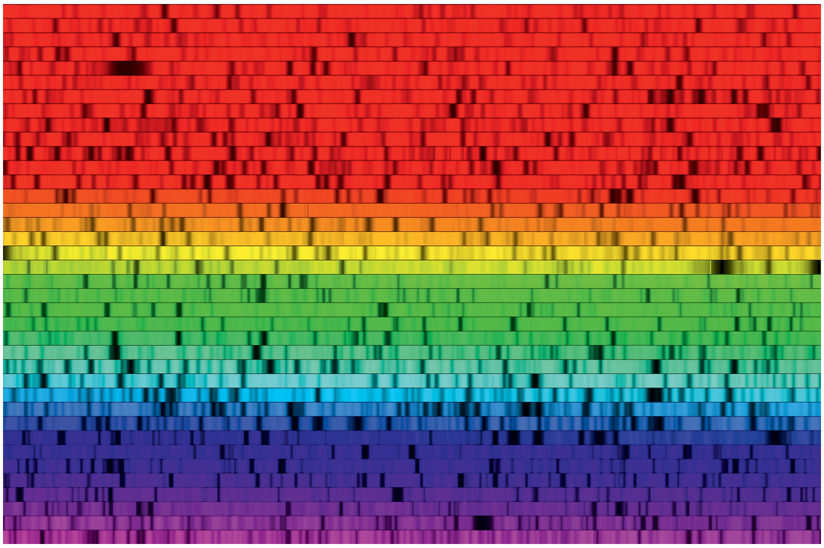
Their gravitational force attracted normal gas particles. These collected in a well like marbles, and the gas compacted to form the first stars and galaxies. Without the midwifery of the dark matter, there would probably be no galaxies or stars.

According to the conventional school of thought, the large galaxies like our Milky Way didn't form to full size. Rather, there were initially smaller subunits that collided, merged and slowly grew. In this so-called hierarchical formation scenario, large galaxies emerge only in a later phase of the universe.

In recent years, however, astronomers have found more and more large galaxies in the infant universe. "The idea that small galaxies have been the most important building blocks of the large galaxies is a myth," says Rix. Two-thirds of all stars in the Milky Way only formed during the past seven to eight billion years, for example, and thus can't originate from early mergers. The likely scenario is that only around 10 percent of the stars in the Milky Way originate from what

Photo: ESA/Gaia/CC BY-SA 3 IGO





Above: The sky survey: The European space probe Gaia, which was launched in December 2013, is to chart the complete sky in the visible spectrum with very high accuracy. The scout covers more than 100 billion stars in our Milky Way. The photo shows the inventory catalog of the galaxy. The two hazy spots on the right-hand side of the lower part of the image are our two neighboring galaxies, the Large and the Small Magellanic Clouds

Left: Rainbow: The light of a star is broken down into its detailed colors, shown here by lines. Each of the dark stripes represents an absorption line that originates from a specific chemical element. The astronomers use such a spectrum to find out which material the star is composed of and when it was formed.

Graphic: Maria Bergemann/MPI for Astronomy

had previously been small building-block galaxies. The Milky Way probably formed almost “in one piece” in one of these gravitational traps of dark matter.

Computer simulations like those that theoretician Greg Stinson computes at the Max Planck Institute for Astronomy, for example, show that gas from the outer regions initially streams into the gravitational wells of dark matter, where it collects in a turbulent disk. The turbulence from back then still hasn’t completely subsided and is reflected in the thick disk, which thus finds a simple explanation.
This doesn’t mean, however, that the swallowing up of small galaxies played no role at all in the evolution of the Milky Way. On the contrary: these processes are evident even now.

Just over ten years ago, astronomers in Heidelberg investigated a small globular star cluster 75,000 light-years away called Palomar 5. They discovered that it orbits the Milky Way, passing through its disk again and again as it does so. On its travels, stars were pulled out of the cluster and now reside in two tails around 15,000 light-years in length, which are also known as stellar streams. Computer models predict that Palomar 5 will dive into the Milky Way again in 100 million years and probably dissolve completely.

These stellar streams are extremely difficult to find because, at first glance, their members don’t differ from the other stars in the Milky Way. They can

be found only by determining the chemical composition and especially the spatial motion of as many stars as possible. The stripped-off remnants of what used to be the companion galaxy then become recognizable, similar to a shoal of fish in the ocean. They can be detected only in the data of modern sky surveys.

The scientists are currently aware of half a dozen or so stellar streams. The newest members are the Ophiuchus stream, named after the Ophiuchus constellation in which it was discovered, and the Sagittarius stream, the first and biggest stream known, located in the eponymous constellation. The latter forms the tidal debris tail of a dwarf galaxy that orbits the Milky Way on an orbit that is almost perpendicular to the center plane.

The Max Planck astronomers were recently able to record this stellar stream in unprecedented detail with their PanSTARRS sky survey. PanSTARRS has been running on Mount Haleakal in Hawaii for five years. A 1.8-meter telescope equipped with the world's largest digital camera, with 1.4 billion pixels, records three-quarters of the celestial sphere visible from Hawaii every four months.

One feature of such analyses is that they allow the merger and its effects on the Milky Way to be studied in detail. There is, however, a second aspect that makes the stellar streams of interest to cosmologists: their members move on broad trajectories outside the Milky Way through its halo, where they are also subjected to the gravitational force exerted by the dark matter.

With the aid of computer simulations, the distribution of this invisible mass can be computed from the mo-

Top: Cosmic detectives: Maria Bergemann and Hans-Walter Rix from the Max Planck Institute for Astronomy in Heidelberg are trying to get to the bottom of how the galaxies evolved. Our Milky Way serves as their "model organism."

Bottom: Birth in a computer: Theoreticians like Greg Stinson reproduce the birth of entire galaxies in complex simulations. The computations show that gas streams into the gravitational wells of dark matter and collects in a turbulent disk.

Photos: Thomas Hartmann (top), Stinson et al. (2013) "MaGICC" (bottom)

tions of the stars. “If we do this for several stellar streams moving on different trajectories, we can even determine the spatial distribution of the dark matter,” says Hans-Walter Rix.

Rix’s team is very well integrated into this pioneering research through its participation in the PanSTARRS sky survey. The astronomers additionally hope that the data from the *Gaia* space telescope of the European Space Agency ESA, which was launched at the end of 2013, will take them a giant leap forward. *Gaia* is currently recording the positions, motions, brightness and colors of one billion stars in the Milky Way.

Max Planck astronomers are working on the classification of the stars. In one to two years, they will be able to analyze the first datasets of the mission. “We hope this will lead to the discovery of five to ten new stellar streams,” says Rix. And who knows what surprises this treasure trove of data still has in store. ◂

TO THE POINT

- **Our Milky Way serves the astronomers in Hans-Walter Rix’s team as a kind of Rosetta Stone that they use to study the evolution of galaxies.**
- **By determining the properties of as many stars as possible and entering them into computer models, the researchers discover the past history of the galaxies.**
- **The textbook teaching that the stars in the galaxy are spread over a thin and a thick disk can no longer be maintained. The theory stating that our Milky Way collided with another large galaxy at some time in the past, leading to the formation of the thick disk we observe, will probably also have to be discarded.**
- **The team headed by Rix has also exposed what some believe – that large galaxies grew gradually by colliding with many small stellar clusters – to be a myth. Two-thirds of all stars in the Milky Way only formed during the past seven to eight billion years, for example, and thus cannot originate from early mergers.**

GLOSSARY

European Extremely Large Telescope: This project of the European Southern Observatory (ESO) is currently being built on Cerro Armazones, a mountain that rises to 3,000 meters in the Chilean Andes. The E-ELT will have a main mirror constructed from 798 hexagonal elements and measuring 39 meters in diameter, and will be the largest telescope on Earth on its planned completion date in 2024.

Sloan Digital Sky Survey: The SDSS is a survey that will cover a quarter of the sky. Its objective is to record the positions and brightness of more than 100 million celestial objects at five wavelengths. It will also acquire spectra from individual objects.

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Call for Nominations
Max Planck Research Award 2016

The International Research Award of the Alexander von Humboldt Foundation and the Max Planck Society

The Alexander von Humboldt Foundation and the Max Planck Society jointly confer the Max Planck Research Award, which is funded by the German Federal Ministry for Education and Research, on exceptionally highly-qualified German and foreign scientists. The researchers are expected to have already achieved international recognition and to continue to produce outstanding academic results in international collaboration – not least with the assistance of this award. Every year, two research awards are conferred on internationally renowned scientific researchers. One of the awards should be given to a researcher working in Germany and the other to a researcher working abroad. As a rule, each Max Planck Research Award is endowed with 750,000 Euros. Nominations of qualified female scientific researchers are especially welcome. On an annually-alternating basis, the call for nominations addresses areas within the natural and engineering sciences, the life sciences, the humanities and the social sciences. The Max Planck Research Award 2016 will be conferred in the area of life sciences in the subject

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The Rectors/Presidents of German universities or research organisations and the scientific heads of institutes of these organisations are eligible to nominate candidates. Nominations must be submitted to the Alexander von Humboldt Foundation. Applications by prospective candidates themselves are not possible. The deadline for nominations is 15 January 2016.

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